

THE IONIZATION HISTORY OF THE INTERGALACTIC MEDIUM: FINAL REPORT FOR GRANT NASA ATP NAG5-10232 (FORMERLY NAG5-4236)

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1. PROJECT DESCRIPTION

The funded project sought a unified description of the ionization, physical structure, and evolution of the intergalactic medium (IGM) and quasar intervening absorption systems. We proposed to conduct theoretical studies of the IGM and QSO absorbers in the context of current theories of galaxy formation, developing and using numerical and analytical techniques aimed at a detailed modeling of cosmological radiative transfer, gas dynamics, and thermal and ionization evolution. The ionization history of the IGM has important implications for the metagalactic UV background, intergalactic helium absorption, 21-cm tomography, metal absorption systems, fluctuations in the microwave background, and the cosmic rate of structure and star formation.

All the original objectives of our program have been achieved, and the results widely used and quoted by the community. Indeed, they remain relevant as the level and complexity of research in this area has increased substantially since our proposal was submitted, due to new discoveries on galaxy formation and evolution, a flood of high-quality data on the distant universe, new theoretical ideas and direct numerical simulations of structure formation in hierarchical clustering theories. The dawning of the epoch of galaxies, the physics of the interplay between early galaxy formation and the intergalactic medium, and possible observational probes of the end of the "dark ages" remain some of the most debated topics in observational cosmology. The duration of the program was extended beyond the original three years as the PI took a one-year sabbatical in the UK and afterwards moved to the University of California Santa Cruz. A graduate student, C. Porciani, has been funded by this proposal. Below is a list of some of the most recent re-

sults obtained.

2. PHYSICAL PROPERTIES OF THE LYMAN ALPHA FOREST

Avery Meiksin and Mike Norman studied the origin and physical nature of the Ly α forest absorption systems as found in hydrodynamical simulations of the IGM in a standard Cold Dark Matter cosmology (Zhang et al. 1998). The structures of the systems that give rise to the Ly α forest span a wide range in morphologies. At the cosmological average density, the characteristic morphology is cell-like with underdense regions separated by overdense sheet-like partitions. The lowest density contours tend to enclose amorphous, isolated regions. They found that the principal structures of the IGM are in place by $z = 5$, with the evolution in the IGM absorption properties due primarily to the expansion of the universe and the changing intensity of the photoionizing background radiation field. Virtually all the baryons in the simulation fragment into structures that we can identify with discrete absorption lines, with at most 5% remaining in a smoothly distributed component (the Gunn-Peterson effect). Given reasonable assumption on the spectrum of the ionizing UV background, the simulations were able to reproduce the statistics of the carbon and silicon measurements of the Ly α forest at $z = 3$ and the intergalactic He II opacity measurements of *HST* and *HUT*.

3. THE TEMPERATURE OF THE IGM

Numerical N-body/hydrodynamics simulations of structure formation in the IGM, within the framework of CDM-dominated cosmologies have provided a definite picture for the origin of the Ly α forest, one of an interconnected network of sheets and filaments with virialized systems (halos) located at their points of intersection. Most simula-

tions to date assume that the IGM is photoionized and photoheated by a UV radiation background close to that inferred from quasars (Madau, Haardt, & Rees 1999). The width of the lines, as measured by the b parameter of a Voigt profile, is set by thermal broadening, peculiar velocities, and Hubble expansion across the filaments. While the first simulations showed good agreement with the observed line statistics, more detailed studies at higher numerical resolution have revealed a serious conflict with the data: the models predict median values for the b distribution of about 20 km s^{-1} at $z = 3$, compared with the observed median of 30 km s^{-1} . One possible way to restore the agreement with the observations is to increase the temperature of the IGM, adding to the thermal broadening. We pointed out (Madau & Efstathiou 1999) that Compton heating of intergalactic gas by the hard X-ray background (XRB) may help to resolve this discrepancy in underdense regions. The rate of gain in thermal energy by Compton scattering will dominate over the energy input from hydrogen photoionization if the XRB energy density is $\sim 0.2 x / \langle \epsilon \rangle$ times higher than the energy density of the UV background at a given epoch, where x is the hydrogen neutral fraction in units of 10^{-6} and $\langle \epsilon \rangle$ is the mean X-ray photon energy in units of $m_e c^2$. The numerical integration of the time-dependent rate equations showed, however, that in popular models for the redshift evolution of the extragalactic background radiation this effect was not large enough to match the observations. Perhaps a more promising mechanism that could increase the line-width involves radiative transfer effects during the (late) reionization of helium. As discussed below, a major effort has been devoted to develop a radiative transfer code for treating thermal effects during the inhomogeneous reionization.

4. SIMULATING INHOMOGENEOUS REIONIZATION

A key requirement for numerical simulations of inhomogeneous reionization is an efficient algorithm for computing the radiation field $J_\nu(\vec{x})$ in three spatial dimensions given an arbitrary distribution of absorbers and sources, both point and diffuse (e.g., recombina-

tion radiation). In principle, this is accomplished by solving the equation of radiative transfer for the monochromatic intensity I_ν . However, since I_ν is a function of seven variables ($t, \vec{x}, \vec{\Omega}, \nu$), this is impractical on current computers if the intensity needs to be evaluated many times over the course of a hydrodynamical calculation. For this reason, we have been exploring physically motivated approximations to the transfer equation which retain the essential physics while being numerically economical.

Norman, Paschos & Abel (1998) developed a hybrid method that decomposes the radiation field into point source and diffuse components. The point source radiation field is attenuated along radial rays, while the diffuse radiation field is computed by solving the zeroth and first radiation moment equations field with variable Eddington factor closure. In the limit of small (compared to the horizon) volumes, the two moment equations can be simplified and combined into a single nonlinear elliptic equation for the diffuse field. The elliptic equation can be solved using a multigrid algorithm.

In Abel, Norman, & Madau (1999) a numerical method that solves the radiative transfer around point sources within a three dimensional cartesian grid was developed. The method is energy conserving independently of resolution: this ensures the correct propagation speeds of ionization fronts. We described the details of the algorithm, and computed as first numerical application the ionized region surrounding a miniquasar in a cosmological density field at $z = 7$.

5. RADIO SIGNATURES OF HI AT HIGH REDSHIFT

The emission of 21-cm radiation from a neutral intergalactic medium (IGM) at high redshifts has been discussed in a paper (Tozzi et al. 2000) in connection with the thermal and ionization history of the universe. The physical mechanisms that make such radiation detectable against the cosmic microwave background include Lyman-alpha coupling of the hydrogen spin temperature to the kinetic temperature of the gas and preheating of the IGM by the first generation of stars and quasars. Three different signatures were in-

investigated in detail: (a) the fluctuations in the redshifted 21-cm emission induced by the gas density inhomogeneities that develop at early times in cold dark matter (CDM) dominated cosmologies; (b) the sharp absorption feature in the radio sky due to the rapid rise of the Lyman-alpha continuum background that marks the birth of the first UV sources in the universe; and (c) the 21-cm emission and absorption shells that are generated on several Mpc scales around the first bright quasars. Future radio observations with the Giant Metrewave Radio Telescope and the Square Kilometer Array may shed light on the power spectrum of density fluctuations at $z > 7$, and map the end of the “dark age”, i.e. the transition from a neutral universe to a ionized one populated with radiation sources.

6. PHOTON CONSUMPTION IN MINIHALOS DURING REIONIZATION

The process of reionization and its impact on several key cosmological issues (from the role it plays in allowing collapsed objects to cool and make stars, to determining the small-scale structure in the temperature fluctuations of the CMB) has recently received much theoretical attention, and has been studied by several authors using semi-analytic models and three-dimensional numerical simulations. In general, these works aim to follow the time evolution of the filling factor of ionized (H II) regions, based on some input prescriptions for the emissivity and spectra of the ionizing sources.

More recent works have focused on the increased rate of recombinations in a clumpy medium relative to a homogeneous one. These studies have left significant uncertainties on the details of how reionization proceeds in an inhomogeneous medium. Since the ionizing sources are embedded in dense regions, one might expect that these dense regions are ionized first, before the radiation escapes to ionize the low-density IGM. Alternatively, most of the radiation might escape from the local, dense regions along low column density lines of sight. In this case, the underdense ‘voids’ are ionized first, with the ionization of the denser filaments and halos lagging behind.

At the earliest epochs of structure for-

mation in CDM cosmologies the smallest nonlinear objects are the numerous small halos that condense with virial temperatures between the cosmological Jean temperature and $\sim 10^4$ K. Such “minihalos” are not yet fully resolved nor is the process of their photoevaporation captured in large-scale three-dimensional cosmological simulations. In Haiman et al. (2001) we have used semi-analytic methods combined with three-dimensional numerical simulations of individual photoevaporating minihalos to (1) quantify the importance of high-redshift minihalos as sinks of ionizing photons; and (2) assess whether by extrapolating to early times the known population of galaxies and quasars a sufficient number of UV photons are produced for hydrogen reionization. If reionization occurs at sufficiently high redshifts ($z_r \gtrsim 20$), the intergalactic medium is heated to $\sim 10^4$ K and most minihalos never form. On the other hand, if $z_r \lesssim 20$ as it appears more likely, then a significant fraction ($\gtrsim 10\%$) of all baryons have already collapsed into minihalos, and are subsequently removed from the halos by photoevaporation as the ionizing background flux builds up. This process requires a significant budget of ionizing photons, about 10–20 of them per background hydrogen atom. This exceeds the production by a straightforward extrapolation back in time of known quasar and galaxy populations by a factor of up to ~ 10 and ~ 3 , respectively (Haiman et al. 2001).

7. THE EARLIEST LUMINOUS SOURCES

Prior to complete reionization at redshift z_r , sources of ultraviolet radiation will be seen behind a large column of intervening gas that is still neutral. In this case, because of scattering off the line-of-sight due to the diffuse neutral IGM, the spectrum of a source at $z_{em} > z_r$ should show the red damping wing of the Gunn-Peterson absorption trough at wavelengths longer than the local Ly α resonance, $\lambda_{obs} > \lambda_\alpha(1 + z_{em})$, where $\lambda_\alpha = c/\nu_\alpha = 1216$ Å. At $z_{em} \gtrsim 6$, this characteristic feature extends for more than 1500 km s^{-1} to the red of the resonance, and may significantly suppress the Ly α emission line in the spectra of the first generation of objects in the universe. Measuring the shape

of the absorption profile of the damping wing could provide a determination of the density of the neutral IGM near the source.

In Madau & Rees (2000) we focused on the width of the red damping wing – related to the expected strength of the Ly α emission line – in the spectra of very distant QSOs as a flag of the observation of the IGM before reionization. We assessed, in particular, the impact of the photoionized, Mpc-size regions which will surround individual luminous sources of Lyman continuum radiation on the transmission of photons redward of the Ly α resonance, and shown that the damping wing of the Gunn-Peterson trough may nearly completely disappear because of the lack of neutral hydrogen in the vicinity of a bright QSO. The effect of this local photoionization is to greatly reduce the scattering opacity between the redshift of the quasar and the boundary of its H II region. The detection of a strong Ly α emission line in the spectra of bright QSOs shining for $\gtrsim 10^7$ yr cannot then be used, by itself, as a constraint on the reionization epoch. The first signs of an object radiating prior to the transition from a neutral to an ionized universe may be best searched for in the spectra of luminous sources with a small escape fraction of Lyman continuum photons into the IGM, or sources with a short duty cycle (like, e.g., gamma-ray bursts).

8. EARLY METAL ENRICHMENT OF THE IGM

Understanding the origin of the chemical elements, following the increase in their abundances with cosmic time, and uncovering the processes responsible for distributing the products of stellar nucleosynthesis over very large distances are all key aspects of the evolution of gaseous matter in the universe. One of the major discoveries with Keck concerning the IGM has been the identification of metal absorption lines associated with many of the Ly α forest systems at $z = 3 - 3.5$.

From a theoretical perspective, it is unknown whether the existence of heavy elements in the low-density IGM points to an early ($z > 6$) enrichment epoch by low-mass subgalactic systems (Madau, Ferrara, & Rees 2001), or is rather due to late pollution by the population of star-forming galaxies

known to be already in place at $z = 3$. Massive stars will deposit both radiative and mechanical energy into the interstellar medium of protogalaxies. A complex network of ‘feedback’ mechanisms is likely at work in these systems, as the gas in shallow potential is more easily blown away, thereby quenching star formation. To start addressing some of these issues and simulate the process of blow-away, we have developed (Mori, Ferrara, & Madau 2002) a 3D Eulerian code that solves the hydrodynamic equations for a perfect fluid in Cartesian geometry. To deal with very different length scales in our simulation we have adopted a ‘nested grid method’ with six levels of fixed Cartesian grids. The scheme has a wide dynamic range in the space dimension. The results of our simulations show that SN-driven pregalactic outflows may be an efficient mechanism for spreading metals around. Furthermore, as the blastwaves produced by supernova explosions reheat the surrounding intergalactic gas and enrich it with newly formed heavy elements, they appear to inhibit the formation of surrounding low-mass galaxies due to ‘baryonic stripping’ (Scannapieco, Ferrara, & Madau 2002).

PUBLICATIONS FUNDED BY THE PROGRAM

- Scannapieco, E., Ferrara, A., & Madau, P. 2002, "Early Enrichment of the Intergalactic Medium and its Feedback on Galaxy Formation", *ApJ*, 574, 590
- Mori, M., Ferrara, A., & Madau, P. 2002, "Early Metal Enrichment by Pregalactic Outflows: II. Simulations of Blow-Away", *ApJ*, 571, 40
- Metcalf, R. B., & Madau, P. 2001, "Compound Gravitational Lensing as a Probe of Dark Matter Substructure within Galaxy Halos", *ApJ*, 563, 9
- Oh, S. P., Nollett, K. M., Madau, P., & Wasserburg, G. J. 2001, "Did Very Massive Stars Pre-Enrich and Reionize the Universe?", *ApJ*, 562, L1
- Madau, P., Ferrara, A., & Rees, M. J. 2001, "Early Metal Enrichment of the Intergalactic Medium by Pregalactic Outflows", *ApJ*, 555, 92
- Madau, P., & Rees, M. J. 2001, "Massive Black Holes as Population III Remnants", *ApJ*, 551, L27
- Haiman, Z., Abel, T., & Madau, P. 2001, "Photon Consumption in Minihalos during Cosmological Reionization", *ApJ*, 551, 599
- Haehnelt, M., Madau, P., Kudritzki, R., & Haardt, F. 2001, "An Ionizing UV Background Dominated by Massive Stars", *ApJ*, 549, L151
- Keeton, C. R., & Madau, P. 2001, "Lensing Constraints on the Cores of Massive Dark Matter Halos", *ApJ*, 549, L25
- Porciani, C., & Madau, P. 2001, "On the Association of Gamma-ray Bursts with Massive Stars: Implications for Number Counts and Lensing Statistics", *ApJ*, 548, 522
- Madau, P., & Rees, M. J. 2000, "The Earliest Luminous Sources and the Damping Wing of the Gunn-Peterson Trough", *ApJ*, 542, L69
- Porciani, C., & Madau, P. 2000, "Gravitational Lensing of Distant Supernovae in Cold Dark Matter Universes", *ApJ*, 532, 679
- Tozzi, P., Madau, P., Meiksin, A., & Rees, M. J. 2000, "Radio Signatures of H I at High Redshift: Mapping the End of the Dark Age", *ApJ*, 528, 597
- Abel, T., Norman, M. L., & Madau, P. 1999, "Photon Conserving Radiative Transfer around Point Sources in Multi-Dimensional Numerical Cosmology", *ApJ*, 523, 66
- Madau, P., & Efstathiou, G. 1999, "Compton Heating of the Intergalactic Medium by the Hard X-ray Background", *ApJ*, 517, L9
- Haiman, Z., Madau, P., & Loeb, A. 1999, "Constraints from the Hubble Deep Field on High Redshift Quasar Models", *ApJ*, 514, 535
- Madau, P., Haardt, F., & Rees, M. J. 1999, "Radiative Transfer in a Clumpy Universe: III. The Nature of Cosmological Ionizing Sources", *ApJ*,
- Zhang, Y., Meiksin, A., Anninos, P., & Norman, M. L. 1998, "Physical Properties of the Lyman-alpha Forest in a Cold Dark Matter Cosmology", *ApJ*, 495, 63
- Madau, P., Della Valle, M., & Panagia, N. 1998, "On the Evolution of the Cosmic Supernova Rates", *MNRAS*, 297, L17
- Madau, P. 1998, "What Keeps the Universe Ionized at $z = 5$?", in *Molecular Hydrogen in the Early Universe*, ed. E. Corbelli, D. Galli, & F. Palla (Mem. S.A.It.), 471
- Madau, P. 1999, "Starlight in the Universe", *Physica Scripta*, 85, 156
- Norman, M. L., Paschos, P. & Abel, T. 1998, "Simulating Inhomogeneous Reionization", in *Molecular Hydrogen in the Early Universe*, ed. E. Corbelli, D. Galli, & F. Palla (Mem. S.A.It.), 142